

**LEG, VERTICAL, AND JOINT STIFFNESS LEVELS IN REAR-
FOOT AND FORE-FOOT STRIKE LANDINGS**

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Allison Gainer

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LEG, VERTICAL, AND JOINT STIFFNESS LEVELS IN REAR- FOOT AND FORE-FOOT STRIKE LANDINGS

Approved by:

Dr. Edward Botchwey
School of Biomedical Engineering
Georgia Institute of Technology

Dr. Young-Hui Chang
School of Applied Physiology
Georgia Institute of Technology

Dr. Boris Prilutsky
School of Applied Physiology
Georgia Institute of Technology

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LIST OF SYMBOLS AND ABBREVIATIONS

CoM	Center of Mass
FFS	Fore-foot Strike
RFS	Rear-foot Strike
MFS	Mid-foot Strike
GRF	Ground Reaction Force

SUMMARY

Bouncing gait, specifically hopping, running, and jumping, involves a complex combination of legs, joints, muscles, and nerves coordinated to perform simple biomechanical tasks. The findings associated with spring-mass modeling of bouncing gait suggest that hopping and running humans maintain center of mass (CoM) motions by adjusting vertical leg stiffness. Overall, lower extremity stiffness increases with the demands of the activity such as increased hopping frequency, hopping or jumping height, and running speed, which are all associated with increased stiffness. The increase in leg, vertical, and joint stiffness occurs because as more physical demands are imparted on the body, greater resistance to movement is needed to produce controlled movements. Studies comparing fore-foot strike (FFS) and rear-foot strike (RFS) patterns in running and hopping have shown converse results regarding the contribution of knee and ankle joint stiffness levels in preserving total leg stiffness. It is known that fore-foot strike runners generate smaller collision forces than rear-foot strike runners. However, an understanding of how joint stiffness levels differ when in a fore-foot strike pattern compared to a rear-foot strike patterns is unknown. Moreover, it is unclear how leg, vertical, and joint stiffness are affected when humans run at increasing speeds with both a fore-foot and rear-foot strike pattern. Investigations that assess the relationship between strike patterns and changes in velocity are needed in order to clarify joint contributions to changes in performance tasks.

We completed a study on vertical hopping, fore-foot strike running, and rear-foot strike running to determine how ankle and knee joint stiffness values vary across different performance tasks. Throughout the study, leg stiffness remained constant ($P>0.05$) and vertical stiffness increased as the step frequency increased ($P<0.05$). During the fore-foot strike running trials, there were greater increases in ankle joint

stiffness in comparison to knee joint stiffness. This suggests that the knee joint was stiffer than the ankle joint throughout the fore-foot strike running performance. In contrast, there was a greater increase in knee joint stiffness than ankle joint stiffness throughout the rear-foot strike performance, which implies that the ankle joint was stiffer than the knee joint. The changes in joint stiffness levels across the two strike patterns could be attributed to the small decrease in knee excursion and increase in ankle excursion in the fore-foot strike pattern compared to the rear-foot strike pattern. Understanding how these joint-level responses to differentiating in tasks influence the stability of leg stiffness may aid robotic, lower limb prosthetic, and even running shoe design.

CHAPTER 1

INTRODUCTION

Bouncing gait, such as hopping, running, and jumping, involves complex neuromechanical actions of legs, joints, muscles, and nerves coordinated to perform relatively simple biomechanical tasks (e.g., maintaining whole leg stiffness)¹. As a result, bouncing gaits are modeled using a simple spring-mass system to represent center of mass (CoM) dynamics performed to maintain intralimb stability in legged locomotion^{1,2,3,4,5,6}. Our use of the term “stability” here simply refers to the ability of the structure of joint-level variance to minimize the variability of a limb-level variable over repeated locomotor cycles.

The findings associated with spring-mass modeling of bouncing gait suggest that hopping and running humans maintain CoM motions by adjusting vertical leg stiffness. Overall, lower extremity stiffness increases with the demands of the activity such as increased hopping frequency, hopping or jumping height, and running speed, which are all associated with increased stiffness⁴. Vertical and joint stiffness both increase with running velocity and jumping height^{4,7,8,9}. The increase in leg, vertical, and joint stiffness occurs because as more physical demands are imparted on the body, greater resistance to movement is needed to produce controlled movements. In order to produce a greater resistance to movement, stiffness levels are increased.

Total leg stiffness depends directly on the contributions of the ankle, knee, and hip joint stiffness levels. Studies comparing fore-foot strike (FFS) and rear-foot strike (RFS) patterns in running and hopping have shown converse results regarding the contribution of knee and ankle joint stiffness levels in preserving total leg stiffness. In behaviors using a FFS patterns, like vertical and forward hopping, individuals increase ankle stiffness as the frequency increases in order to adjust vertical stiffness^{3,7,10}. In normal hopping, humans increase leg stiffness by proportionally increasing total ankle

stiffness, but also by adopting more extended knee postures at mid-stance as they increase total ankle stiffness and leg stiffness¹. However, compared to sensitivity of vertical stiffness to ankle stiffness, vertical stiffness is relatively insensitive to changes in knee stiffness and hip stiffness. Thus vertical stiffness is mainly determined by ankle joint stiffness during human hopping².

Running involves more variables and is thus more complicated than hopping. Leg stiffness, along with vertical and joint stiffness values, increases as running velocity increases to meet the physical demands needed for performance. As a result, the total stiffness of leg and surface stiffness in series remains the same regardless of the running velocity. Leg stiffness has been reported to remain constant with running velocity up to moderate velocities (~ 5.0 m/s)¹¹. Vertical stiffness increases linearly with the running speed, as ground reaction force (GRF) increases linearly with vertical CoM^{8,12}.

During human running, leg stiffness is mainly modulated by knee stiffness¹¹. However, there has been some confusion about the effect of ankle joint stiffness on leg stiffness as running speed is increased. One study found that both the ankle joint stiffness and joint moment were constant at different running speeds¹². Another study reported an increase in the ankle joint moment while the stiffness of the ankle joint showed a curvilinear pattern (without any significant difference) with the increasing running speed from 2.5 m/s to 6.5 m/s⁸. Other studies have shown that ankle joint stiffness, along with ankle joint moment, increased with the running speed and hopping height^{4,12}.

It is possible that the differing results on the topic of ankle joint stiffness and its influence on leg stiffness are simply due to the lack of controlling foot strike patterns. Most studies suggest that alterations in joint stiffness may be related, in part, to foot strike pattern during landing⁴. 75-80% of shod endurance runners have a RFS pattern, resulting in 20-25% to have a FFS or mid-foot strike (MFS) pattern. As RFS humans run with increasing speed, most will naturally change from the RFS pattern to a FFS pattern. If not controlled within a study, the different nature of human's foot strike patterns makes

the comparison difficult between FFS and RFS pattern running and hopping in place as different joint stiffness levels are needed for each task.

Foot-foot and rear-foot strike running may result in different joint-level stiffness values. It is known that fore-foot strike runners generate smaller collision forces than rear-foot strike runners. However, an understanding of how joint stiffness levels differ when in a fore-foot strike pattern compared to a rear-foot strike patterns is unknown. Moreover, it is unclear how leg, vertical, and joint stiffness are affected when humans run at increasing speeds with both a fore-foot and rear-foot strike pattern. It is also unclear as to why the ankle and knee joints respond differently in adapting to the tasks of FFS running and hopping.

Investigations that assess the relationship between strike patterns and changes in velocity are needed in order to clarify joint contributions to changes in performance tasks. Task performance has the ability to be enhanced with a gain of knowledge about joint level stiffness values in both rear-foot and fore-foot strike patterns. The purpose of this study is to investigate running strike patterns over a range of step frequencies while at a constant running velocity. It was hypothesized that leg stiffness will remain constant across each subject's performance. It was predicted vertical stiffness would increase with the increasing step frequencies. It was hypothesized that the changes in vertical stiffness in fore-foot strike pattern running across varying step frequencies would be influenced by alterations made mainly by ankle joint stiffness (in comparison to knee joint stiffness). In contrast, it was hypothesized that the changes in vertical stiffness across varying step frequencies in rear-foot running would be controlled mainly by alterations in knee joint stiffness (compared to ankle joint stiffness).

This gain of knowledge will allow for more efficient strength, power, and eccentric exercise, leading to less energy expenditure and injury. Understanding how joint-level responses to differentiating in tasks influence the stability of leg stiffness may aid robotic, lower limb prosthetic, and even running shoe design. This understanding will

allow for improved design, resulting in reduced collision forces. Reduced collision forces lead to less impact on the knee and ankle joints during differing performance tasks, allowing for enhanced task performance.

CHAPTER 2

METHODS

Ten subjects (five male, five female, 20.6 ± 1.06 years) were recruited to complete a study on the leg stiffness values in rear-foot and fore-foot strike landings. None of the subjects had any prior history of lower extremity injuries. The subjects performed several tasks, including forward hopping on a single limb, vertical hopping on a single limb, and FFS and RFS pattern running. Prior to activity, anatomical measurements were made, including height, leg length, ankle width, and knee width. Retro-reflective markers were placed on anatomical landmarks of the lower extremities (anterior superior iliac spine, posterior superior iliac spine, greater trochanter, thigh segment, lateral femoral epicondyle, shank segment, lateral malleolus, head of the second metatarsal phalangeal joint, calcaneus, and fifth metatarsophalangeal joint).

Five trials of running were collected on each subject. Each running trial consisted of one minute of both FFS and RFS running at a predetermined step frequency and speed. When comparing FFS and RFS running, the subjects performed running at a constant velocity, 2.5 m/s, throughout the entire running performance. However, step frequency was varied (2.5, 2.6, 2.75, 2.9, and 3.0 Hz) at both running strike patterns. The order of each step frequency for both FFS and RFS was randomized across each subject's performance.

Four subjects performed forward hopping on a single limb at 2.0 m/s with a step frequency of 2.2 Hz and vertical hopping on a single limb with a hop frequency 2.2 Hz. After protocol adjustments were made, the following six subjects performed three single limb vertical hopping trials with the hop frequencies of 1.9, 2.2, and 2.5 Hz, respectively. The general protocol and revised protocol are outlined in Table 1 and Table 2 of Appendix A. Step and hop frequency were matched during each trial by the beat of a

metronome. Prior to beginning each trial, it was ensured that the subject visually displayed the correct foot strike pattern needed for the trial.

3-D kinematics of the lower limbs was collected using a six-camera motion analysis system (120 Hz, Vicon Motion Systems; Los Angeles, CA). Ground reaction force data was collected using a force platform (AMTI; Watertown, MA, USA). Leg stiffness (k_{leg}) was measured during the stance phase and was calculated as the ratio between the maximum GRF and the change in vertical leg length^{4,11,13}. CoM displacement was determined through the double differentiation of the vertical GRF. Vertical stiffness (k_{vert}) was calculated to describe the linear movements occurring in the vertical direction and can be described as the ratio between maximum GRF and the maximum vertical displacement of the CoM^{4,11,13}. Inverse dynamics analysis was used to calculate joint moments during ground contact. The average joint stiffness (k_{joint}) was calculated as ratio between the change in joint moment and the change in joint angle². Leg, vertical, and joint stiffness equations used in this study can be found in Table 3 of Appendix A.

One-way ANOVA was used for statistical analysis of leg, vertical, and within vertical hopping, fore-foot, and rear-foot strike landings; the test assessed whether the means across each step frequency were significantly different ($\alpha=0.05$). Repeated measures ANOVA was used for statistical testing between FFS and RFS patterns. Repeated measures ANOVA controls for the variability between subjects and thus was the best statistical method to determine if there were significant differences between foot strike pattern and step frequency ($\alpha=0.05$).

CHAPTER 3

RESULTS AND DISCUSSION

Results

After collecting data on four subjects, data analysis was performed to determine and ensure the validity of the collected data. In the process, the trial of forward hopping on a single limb was removed. Two extra trials of vertical hopping were added to the protocol, resulting in the total of three 30-second trials of vertical hopping at the hopping frequencies of 1.9, 2.2, and 2.5 Hz. The remaining six subjects performed three vertical hopping trials. The reasoning behind adding two additional trials of vertical hopping lies within the data analysis of vertical and joint stiffness values across the hopping trials. Analysis on the effect of joint stiffness levels on overall lower extremity stiffness in vertical hopping will act as a baseline for the study, as the impact of ankle, knee, and hip joint stiffness levels are already widely understood in vertical hopping.

Validation of fore-foot and rear-foot strike patterns was found by looking at the ankle joint angle across a step cycle and can be in Figure 1 of Appendix B. During the vertical hopping trials, vertical stiffness increased as hop frequency increased ($P < 0.05$). On average, the ankle joint stiffness increased by 2.008-fold between the lowest step frequency (1.9 Hz) and the highest step frequency (2.5 Hz). Knee stiffness increased by 1.539-fold but hip stiffness remained unchanged ($P > 0.05$). Results from the ANOVA statistical testing can be found in Table 4 of Appendix B. Vertical and joint stiffness values can be found in Figures 2-5 of Appendix B.

During both the FFS and RFS running performance, leg stiffness remained constant ($P > 0.05$) and vertical stiffness increased as the step frequency increased ($P < 0.05$). During the fore-foot strike running performance, ankle joint stiffness increased by 1.271-fold between the lowest step frequency (2.5 Hz) and the highest step frequency

(3.0 Hz). Knee stiffness increased by 1.041-fold and hip stiffness increased by 1.792-fold. However, during the rear-foot strike running performance, ankle joint stiffness increased by 1.319-fold between the lowest step frequency (2.5 Hz) and the highest step frequency (3.0 Hz). Knee stiffness increased by 1.515-fold while hip stiffness increased by 1.542-fold. Results from the ANOVA statistical testing can be found in Table 5 of Appendix B. Leg, Vertical, and joint stiffness values for fore-foot and rear-foot strike running can be found in Figures 6-13 of Appendix B.

Discussion

Along with the ankle joint angle, the ground reaction forces associated with both FFS and RFS running can confirm that each subject followed the correct strike patterns throughout performance. Force differences between the strike patterns can be seen during initial contact time, as differing ground reaction forces values are associated with each strike pattern. The GRFs associated with both FFS and RFS running can be found in Figure 14 of Appendix B. Overall, lower extremity stiffness increased with the increasing demands of all tasks throughout the study, as increased hop and step frequency are associated with increased stiffness.

In single leg vertical hopping, the vertical stiffness increased with increasing step frequency. Lower extremity stiffness increased as the frequency of the activity increased, which may be necessary to resist collapse of the lower extremity during the early phase of landing and allow for maximum energy return during the propulsive phase^{4, 7}. Since the ankle joint underwent the largest displacement in response to the increasing step frequencies, the knee stiffness was greater than the ankle stiffness. This could suggest the ankle stiffness has more influence on overall vertical stiffness. It is possible that lower extremity stiffness is most sensitive to ankle stiffness because of the geometry of the leg during vertical hopping³.

In both fore-foot and rear-foot strike running, leg stiffness remained constant throughout each subject's performance. As each subject ran with increasing step frequencies, the increase in leg spring length was accompanied by an increase in the subject's maximum vertical force. Throughout the running trials, vertical stiffness was always greater than the leg stiffness, as the leg spring length was greater than the CoM displacement. Vertical stiffness was expected to increase across the running performance; increases in force levels of the CoM should mirror increases in vertical stiffness with step frequency.

During the fore-foot strike running trials, there were greater increases in ankle joint stiffness in comparison to knee joint stiffness. This suggests that the knee joint was stiffer than the ankle joint throughout the fore-foot strike running performance. In contrast, there was a greater increase in knee joint stiffness compared to ankle joint stiffness in the rear-foot strike performance, which implies that the ankle joint was stiffer than the knee joint. The changes in joint stiffness levels across the two strike patterns could be attributed to the small decrease in knee excursion and increase in ankle excursion in the fore-foot strike pattern compared to the rear-foot strike pattern. Ankle and knee excursion values can be found in Table 6 of Appendix B.

However, ankle joint stiffness did not remain constant across the rear-foot strike running performance as others studies have shown¹². This could be due to a difference in performance tasks, as previous studies were based off of running at moderate and high speeds. Overall, comparing FFS and RFS running, both ankle joint stiffness and knee joint stiffness increased on a greater level (Table 5 of Appendix B) across the increasing step frequencies in the rear-foot strike running performance. This could be associated with higher ankle and knee joint moment values throughout the rear-foot strike running trials.

Our findings suggest that ankle joint stiffness plays the prominent role in fore-foot strike landings, including vertical hopping and fore-foot strike running. On contrast, knee

joint stiffness plays a prominent role in rear-foot strike landings. However, ankle joint stiffness contributes significantly to rear-foot strike running as step frequency increases at a constant velocity. Hip joint stiffness also acts as a contributing role throughout the running performance, as the increase in hip joint values across increasing step frequencies contributes to the overall increase in lower extremity stiffness. It seems that the ankle or knee joint stiffness may not be the limiting factor in the increase of lower extremity stiffness when running with a FFS and RFS pattern. Thus, there is a need for additional studies to better understand joint-level responses to running strike patterns.

Future Directions

In the future, more closely examining the variation in hip joint stiffness during running may give important insight into the overall increase of lower extremity stiffness with increasing step frequency. Possible limitations of the current study could be the limited range of step frequencies used throughout the running performance. Potential studies could more carefully examine joint stiffness levels by using a more wide range of step frequencies, as a greater variance in step frequency could show more significant results in joint stiffness levels. Other possible limitations could be due to a lack of the correct strike pattern throughout each running trial and the lack of matching step frequency to the beat of the metronome.

APPENDIX A

MATERIALS AND METHODS TABLES AND FIGURES

Table 1. Protocol A

Task:	Time of Trial:	Speed:	Step Frequency:
Vertical Hop	20 sec (3 trials)	N/A	2.2 Hz
Forward Hop	20 sec (3 trials)	2.5 m/s	2.2 Hz
Fore-foot Run	1 min	2.5 m/s	2.5 Hz
Rear-foot Run	1 min	2.5 m/s	2.5 Hz
Fore-foot Run	1 min	2.5 m/s	2.6 Hz
Rear-foot Run	1 min	2.5 m/s	2.6 Hz
Fore-foot Run	1 min	2.5 m/s	2.75 Hz
Rear-foot Run	1 min	2.5 m/s	2.75 Hz
Fore-foot Run	1 min	2.5 m/s	2.8 Hz
Rear-foot Run	1 min	2.5 m/s	2.8 Hz
Fore-foot Run	1 min	2.5 m/s	2.9 Hz
Rear-foot Run	1 min	2.5 m/s	2.9 Hz

This table outlines the general protocol used for collection on the initial four subjects.

Table 2. Protocol B

Task:	Time of Trial:	Speed:	Step Frequency:
Vertical Hop	30 sec	N/A	1.9 Hz
Vertical Hop	30 sec	N/A	2.2 Hz
Vertical Hop	30 sec	N/A	2.5 Hz
Fore-foot Run	1 min	2.5 m/s	2.5 Hz
Rear-foot Run	1 min	2.5 m/s	2.5 Hz
Fore-foot Run	1 min	2.5 m/s	2.6 Hz
Rear-foot Run	1 min	2.5 m/s	2.6 Hz
Fore-foot Run	1 min	2.5 m/s	2.75 Hz
Rear-foot Run	1 min	2.5 m/s	2.75 Hz
Fore-foot Run	1 min	2.5 m/s	2.8 Hz
Rear-foot Run	1 min	2.5 m/s	2.8 Hz
Fore-foot Run	1 min	2.5 m/s	2.9 Hz
Rear-foot Run	1 min	2.5 m/s	2.9 Hz

The table above outlines the general protocol for collection on the remaining six subjects.

Table 3. Stiffness Levels Equations

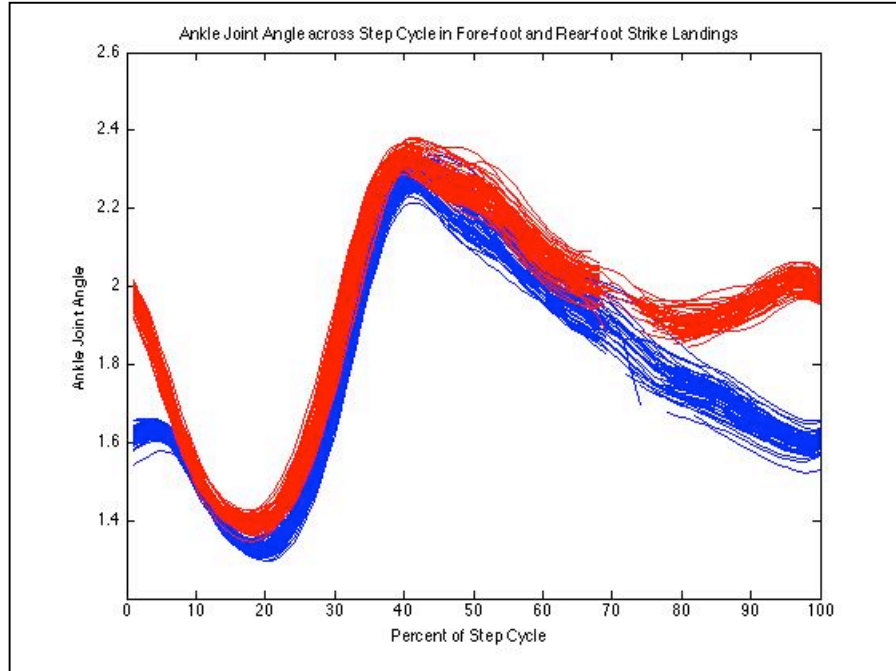
Equation		Reference
$K_{leg} = \frac{F_{max}}{\Delta L}$	(1)	McMahon and Cheng (1990)
$K_{vert} = \frac{F_{max}}{\Delta y}$	(2)	McMahon and Cheng (1990)
$K_{joint} = \frac{J_m}{J_d}$	(3)	Stefanyshyn and Nigg (1998)

The table above displays the equations used to calculated leg, vertical, and joint stiffness values.

APPENDIX B

RESULTS AND DISCUSSION TABLES AND FIGURES

Figure 1. Validation of Strike Patterns across Step Cycles



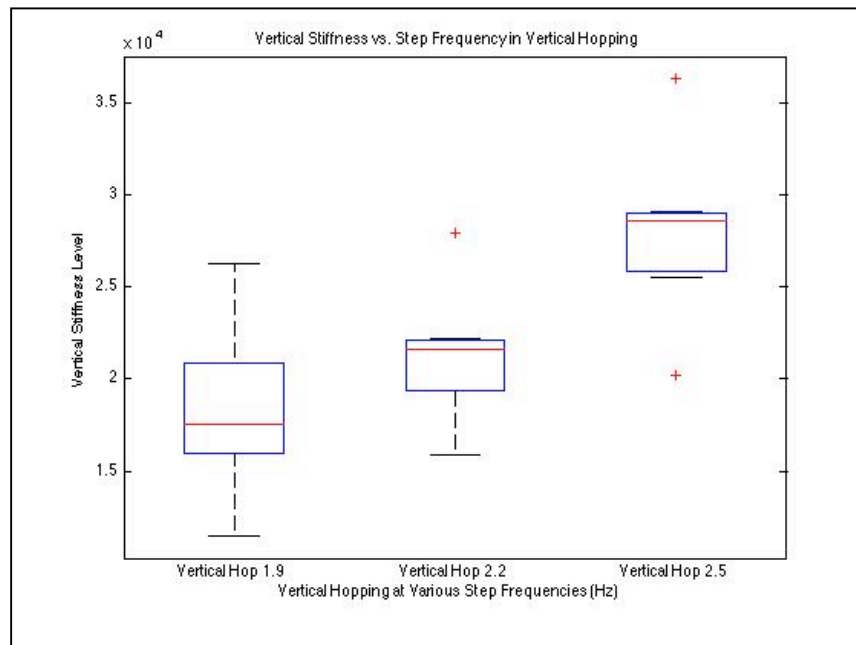
The figure above shows the validation of subjects performing the correct strike pattern when running. Fore-foot strike pattern (red) has an increased ankle joint angle during contact time, as the ankle joint extends to allow the toe to strike the ground first. Rear-foot strike patterns (blue) have a decreased ankle joint angle during contact time, as the ankle joint flexes to allow the heel to strike the ground first.

Table 4. ANOVA Statistical Analysis for Stiffness Levels during Vertical Hopping

Vertical Hopping: Stiffness Levels across Varying Hop Frequencies			
	Hop Frequency: 1.9 Hz	Hop Frequency: 2.5 Hz	
Vertical Stiffness	17580	28610	*
Ankle Joint Stiffness	386.14	775.5	*
Knee Joint Stiffness	-303.53	-467.34	*
Hip Joint Stiffness	131.51	97.27	

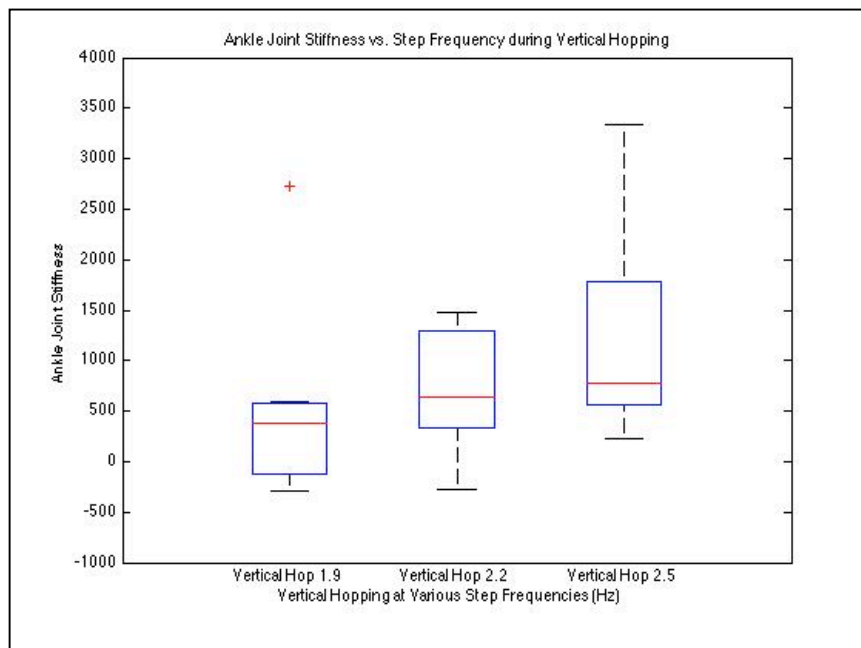
The following table displays the values from ANOVA testing across increasing step frequencies during single leg vertical hopping. Median values are presented. An asterisk (*) denotes a statistically difference between 1.9 Hz and 2.5 Hz hop frequency.

Figure 2. Vertical Stiffness in Vertical Hopping



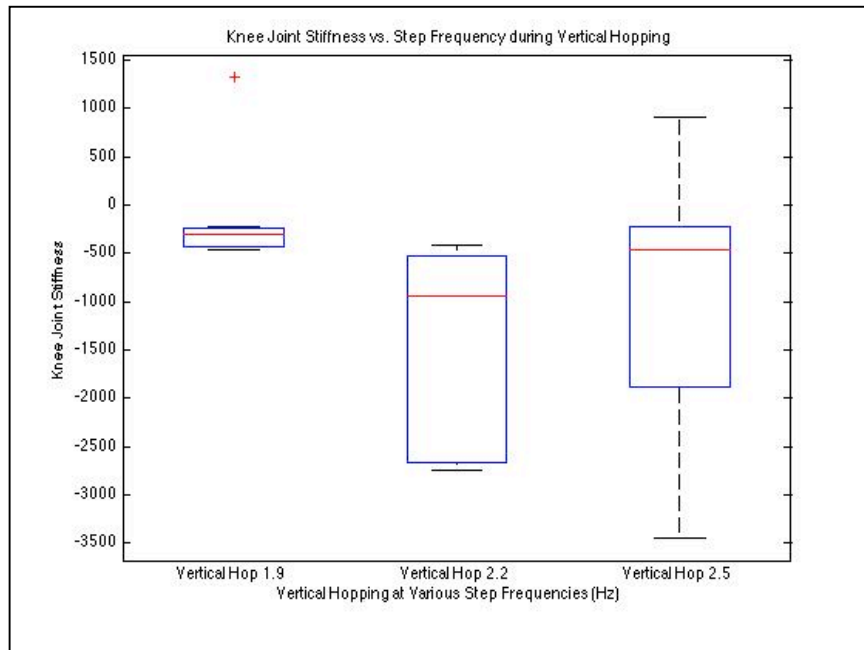
The figure above displays box plots of vertical stiffness across increasing step frequencies during single leg vertical hopping.

Figure 3. Ankle Joint Stiffness in Vertical Hopping



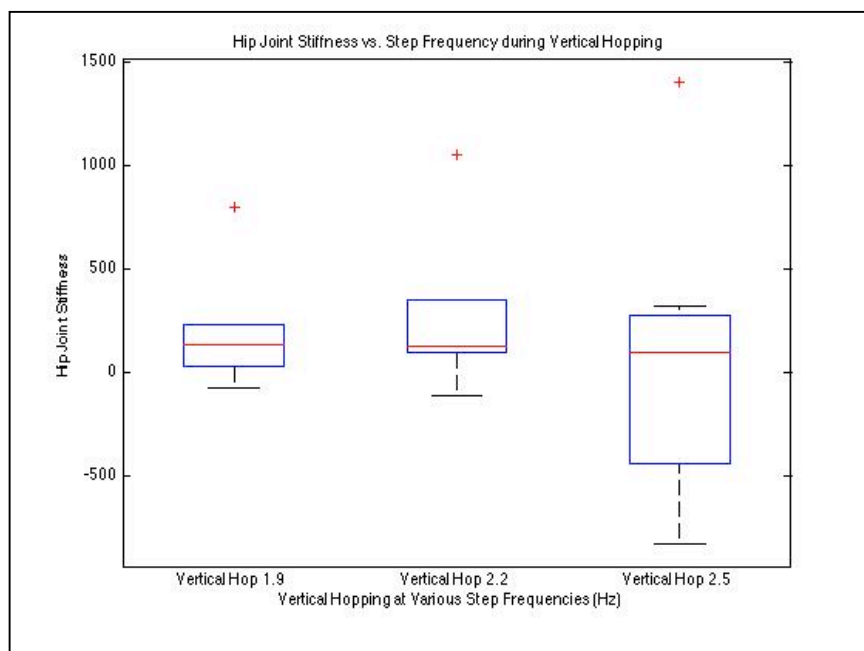
The figure above displays box plots of ankle joint stiffness across increasing step frequencies during single leg vertical hopping.

Figure 4. Knee Joint Stiffness in Vertical Hopping



The figure above displays box plots of knee joint stiffness across increasing step frequencies during single leg vertical hopping.

Figure 5. Hip Joint Stiffness in Vertical Hopping



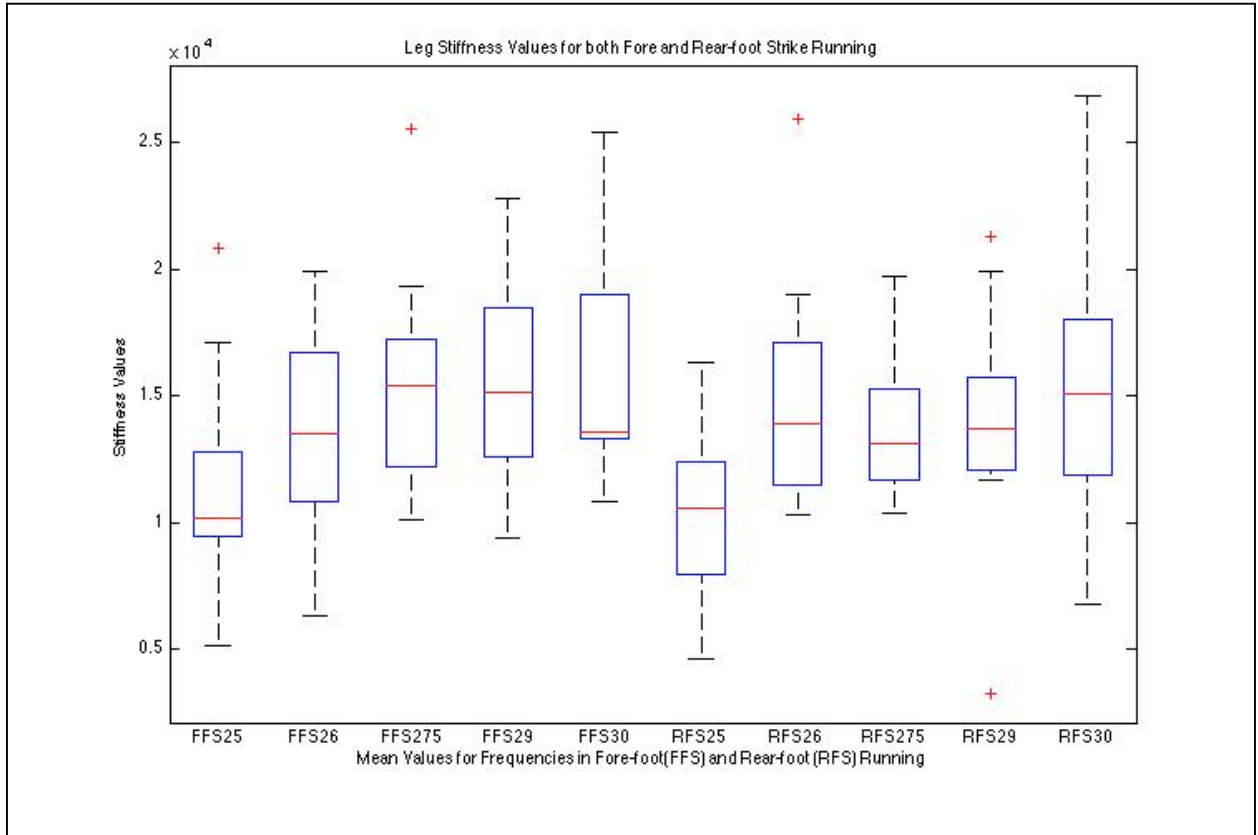
The figure above displays box plots of hip joint stiffness across increasing step frequencies during single leg vertical hopping.

Table 5. ANOVA Statistical Analysis for Stiffness Levels during Running

Running: Stiffness Levels across Varying Step Frequencies			
	Step Frequency: 2.5 Hz	Step Frequency: 3.0 Hz	
Fore-foot Strike Pattern			
Leg Stiffness	10400	13800	
Vertical Stiffness	18600	23700	*
Ankle Joint Stiffness	327.95	416.83	*
Knee Joint Stiffness	-331.73	-345.35	
Hip Joint Stiffness	107.00	191.75	*
Rear-foot Strike Pattern			
Leg Stiffness	11000	13200	
Vertical Stiffness	17400	24600	*
Ankle Joint Stiffness	323.71	426.83	*
Knee Joint Stiffness	-263.15	-398.68	*
Hip Joint Stiffness	107.79	166.23	*

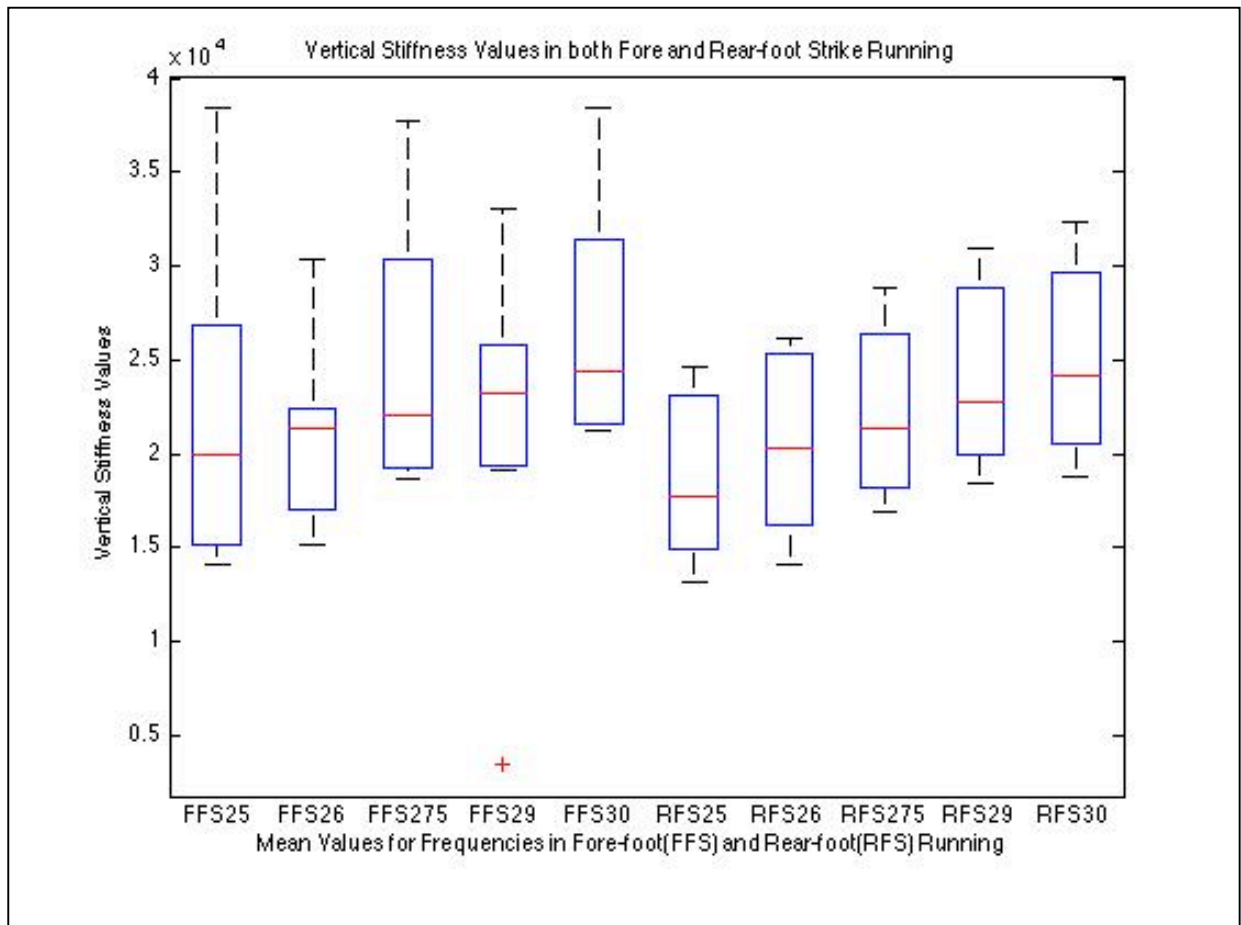
The following table displays the values from ANOVA testing across increasing step frequencies during running. Median values are presented. An asterisk (*) denotes a statistically difference between the 2.5 Hz and 3.0 Hz step frequency running trials.

Figure 6. Leg Stiffness during Running Performance



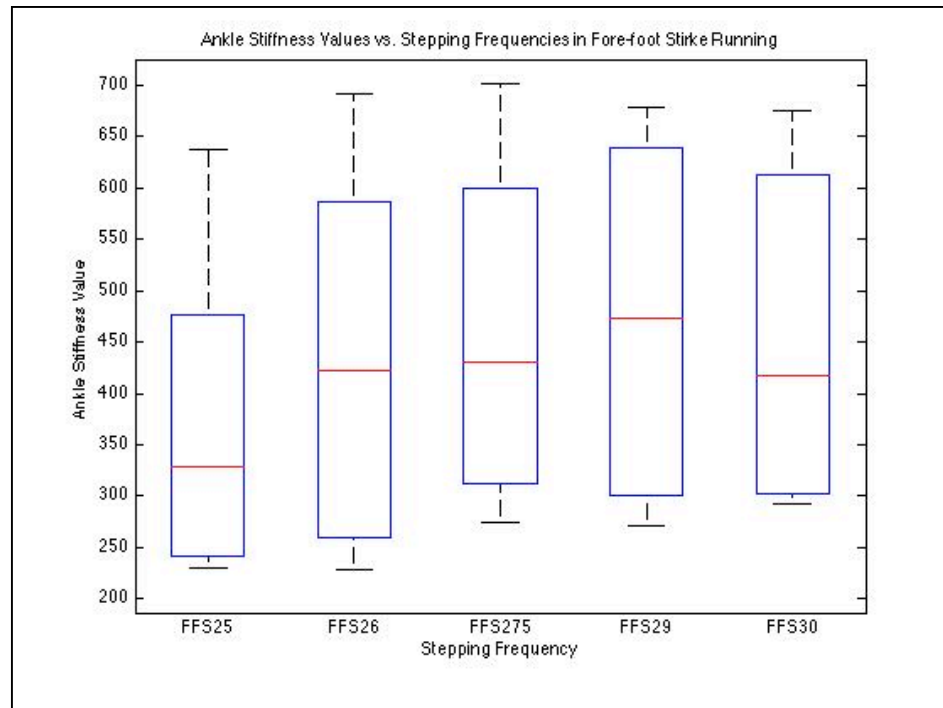
The figure above represents the mean values of leg stiffness across all subjects during both FFS and RFS running performances. Over the course of the entire performance, leg stiffness remained constant ($P > 0.05$).

Figure 7. Vertical Stiffness during Running Performance



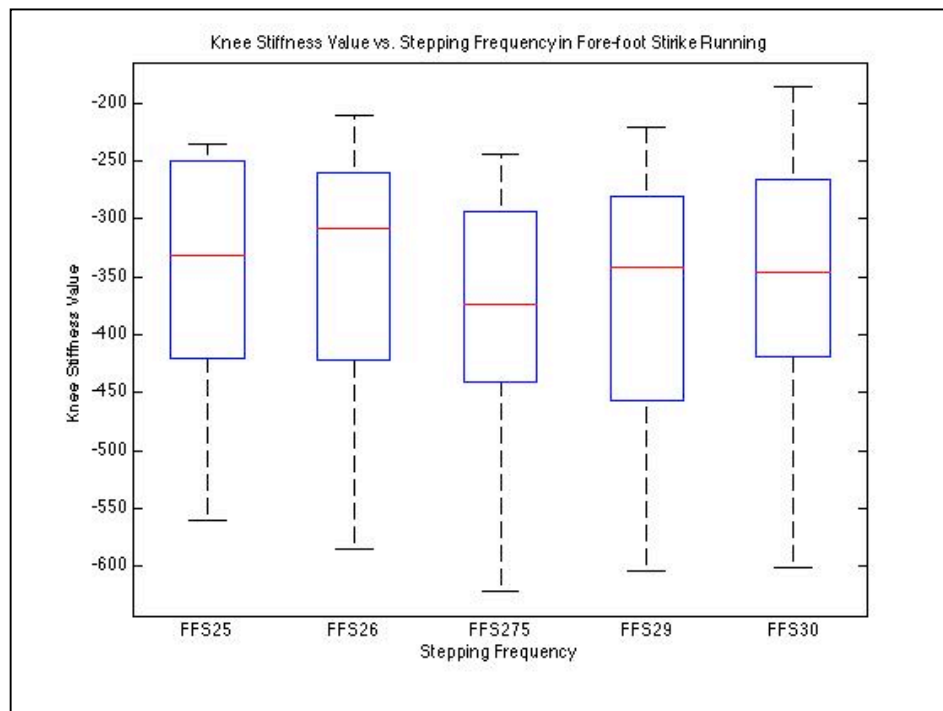
The figure above represents the mean values of vertical stiffness across all subjects during both FFS and RFS running performances. Vertical stiffness increased with increasing step frequency ($P < 0.05$).

Figure 8. Ankle Joint Stiffness in Fore-foot Strike Running



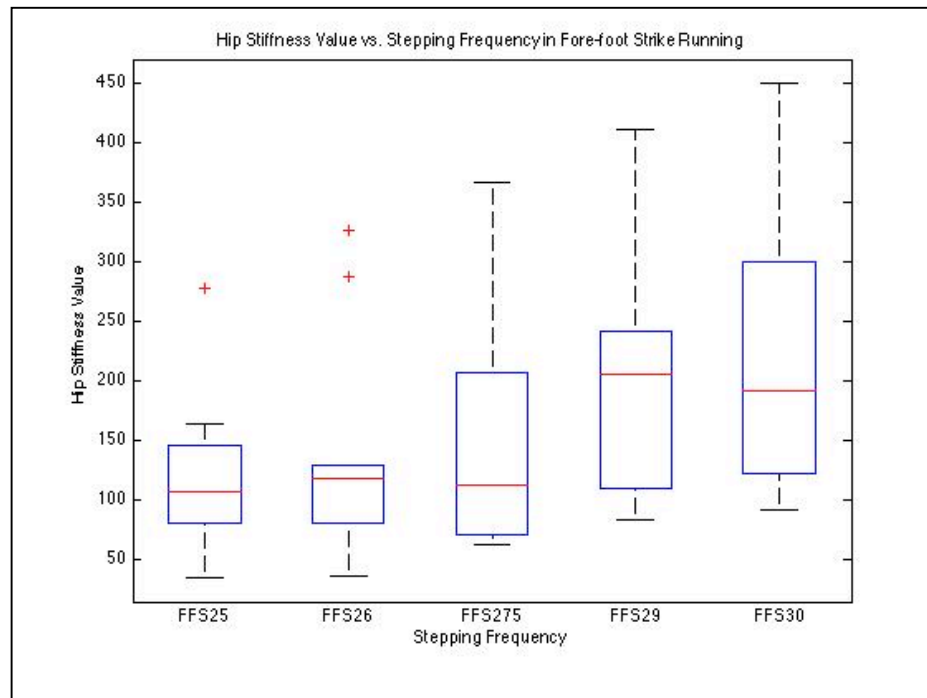
The figure above shows the ankle joint stiffness across increasing step frequencies in fore-foot strike running.

Figure 9. Knee Joint Stiffness in Fore-foot Strike Running



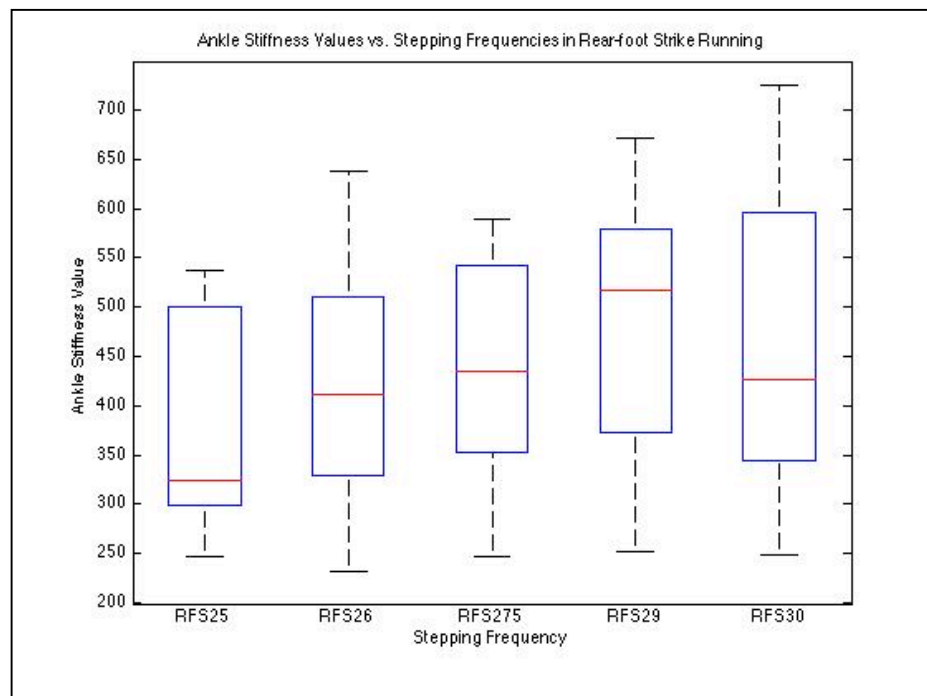
The figure above shows the knee joint stiffness across increasing step frequencies in fore-foot strike running.

Figure 10. Hip Joint Stiffness in Fore-foot Strike Running



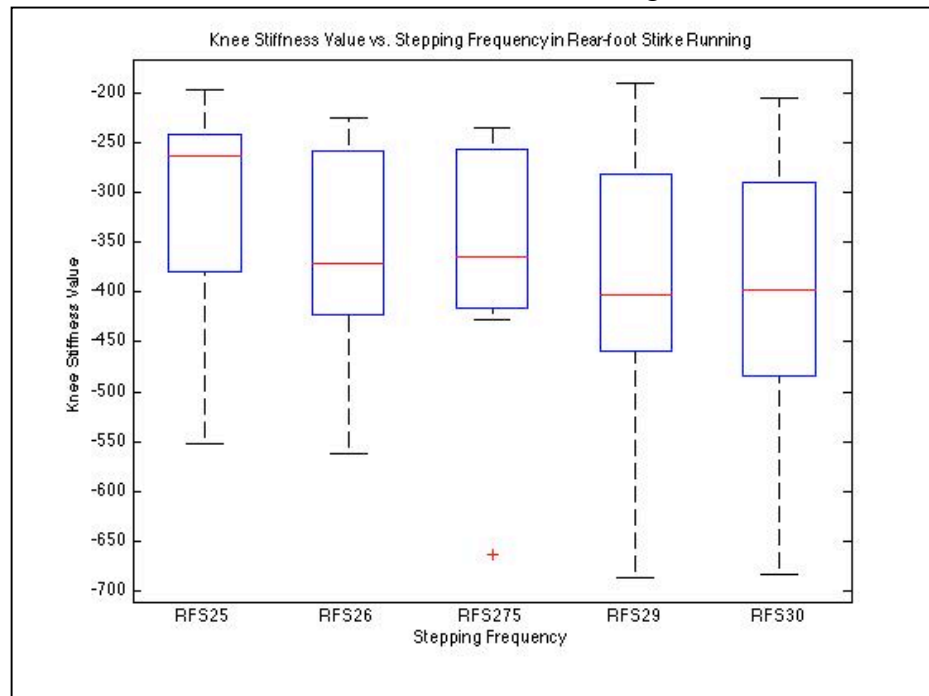
The figure above shows the hip joint stiffness across increasing step frequencies in fore-foot strike running.

Figure 11. Ankle Joint Stiffness in Rear-foot Strike Running



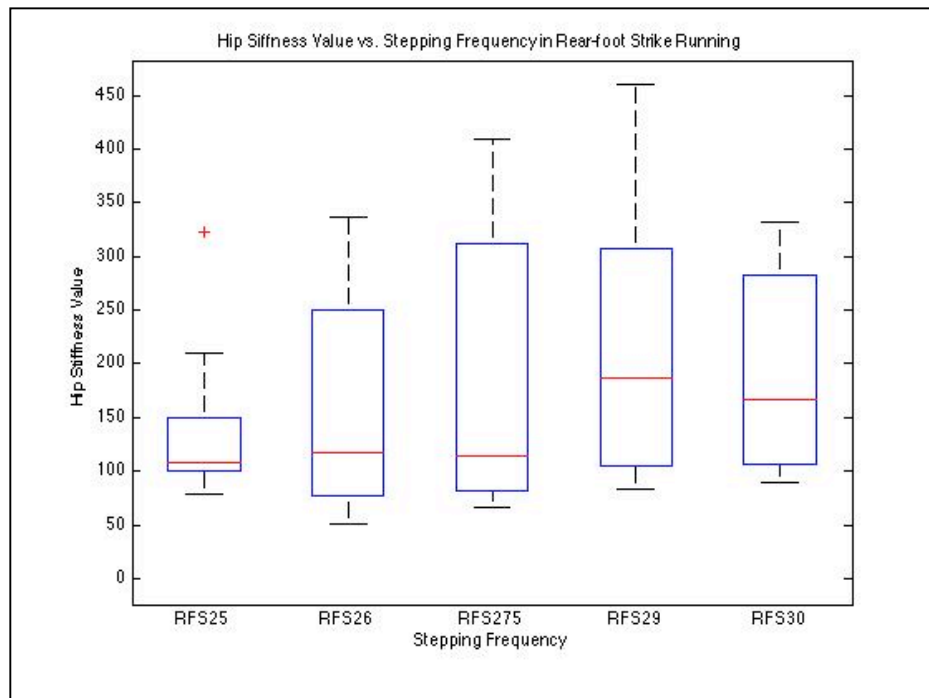
The figure above shows the ankle joint stiffness across increasing step frequencies in rear-foot strike running.

Figure 12. Knee Joint Stiffness in Rear-foot Strike Running



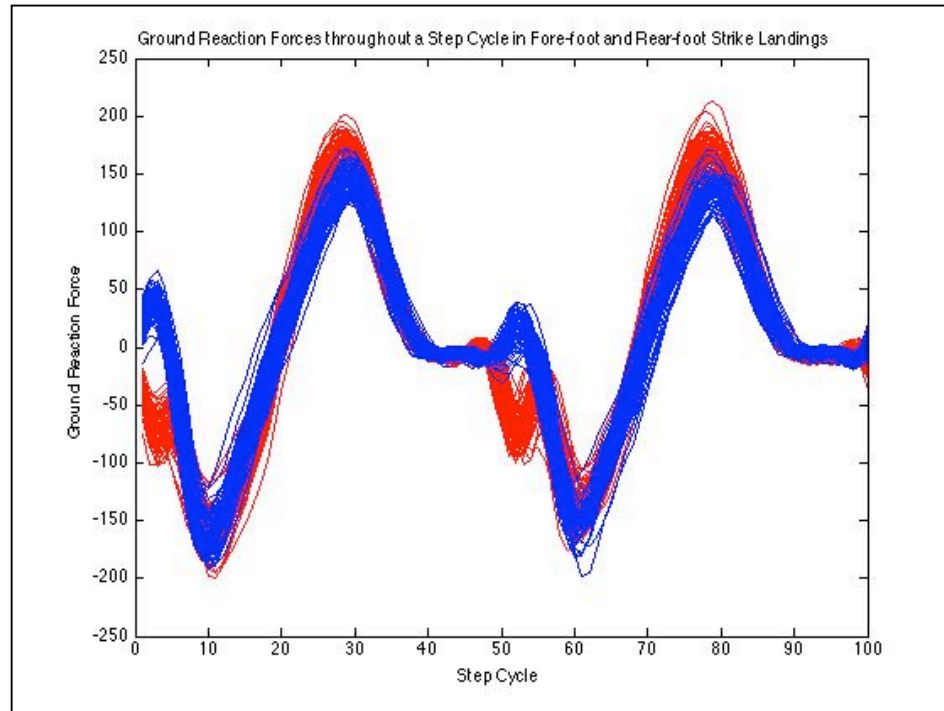
The figure above shows the knee joint stiffness across increasing step frequencies in rear-foot strike running.

Figure 13. Hip Joint Stiffness in Rear-foot Strike Running



The figure above shows the hip joint stiffness across increasing step frequencies in rear-foot strike running.

Figure 14. Ground Reaction Forces in Fore-foot and Rear-foot Strike Running



The following figure shows the ground reaction forces across a running step cycle. The forces associated with fore-foot strike running are indicated in blue while the forces associated with rear-foot strike running are denoted in red.

Table 6. Joint Angle Differences across FFS and RFS Performances

Running: Joint Angle Levels across Varying Step Frequencies				
	Ankle Joint Angle (radians)		Knee Joint Angle (radians)	
	Step Frequency: 2.5 Hz	Step Frequency: 3.0 Hz	Step Frequency: 2.5 Hz	Step Frequency: 3.0 Hz
Fore-foot Strike Pattern	1.7944	1.7318	2.3862	2.4491
Rear-foot Strike Pattern	1.5481	1.5612	2.3757	2.4573

The following table displays the median values from the ankle and knee joint angles across increasing step frequencies during running.

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